

TeV RADIATION FROM THE CRAB NEBULA AND OTHER MATTERS

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ABSTRACT

The detection of the Crab Nebula via the Cherenkov imaging technique places TeV astronomy on a secure observational footing. This paper presents the motivation for TeV observations, a discussion of the atmospheric Cherenkov technique, the experimental details of the Crab Nebula detection, and its scientific implications. The present dilemma of VHE/UHE astronomy is that the Crab appears to be the only source whose showers match theoretical expectations. The situation will be clarified as improved ground-based detectors come on-line with sensitivities matching those of the GRO instruments.

I. SCIENTIFIC MOTIVATION

Gamma rays provide direct information about the highest energy processes which occur in nature. The various bands of the gamma ray portion of the electromagnetic spectrum are shown in figure 1. The instruments of the Gamma Ray Observatory will cover the five decades from 0.1 MeV to 10 GeV with a factor of 10 to 20 improvement over previous satellite instruments; however, the 2000 cm^2 detection area of the highest energy instrument, EGRET, means that only a few photons greater than 10 GeV will be detected. Thus gamma rays of higher energy must be detected via shower techniques, either by means of the Cherenkov light from the cascade particles or by means of the particles themselves. In figure 1 I have indicated the approximate range of the Cherenkov technique, 0.1 to 10 TeV, and the band covered by extensive air shower arrays. Gaps exist between each of these bands. Developing instruments which fill these gaps is a major challenge for gamma ray astronomy above 10 GeV.

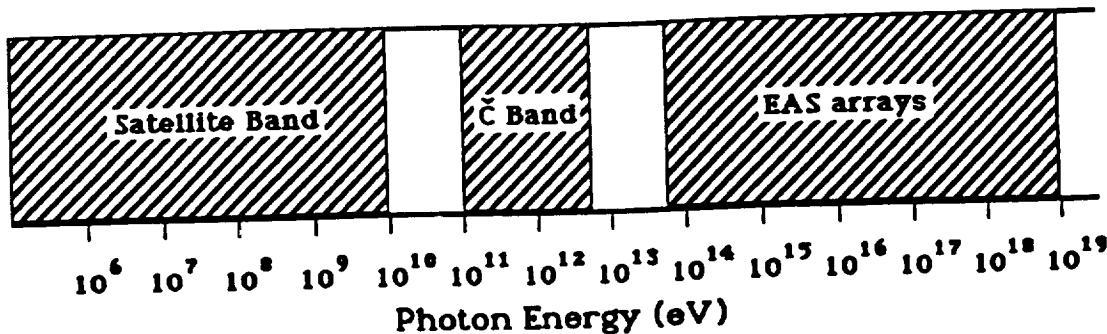


Figure 1. The gamma-ray portion of the electromagnetic spectrum. The cross-hatched portions indicate bands which are covered by present instruments. Gaps exist for ~ 10 to ~ 100 GeV and for ~ 5 to ~ 50 TeV.

Two major motivations for ground-based gamma ray astronomy are the identification of sources of VHE and UHE cosmic rays and understanding relativistic objects.

For energies up to a few times 10^{13} eV, acceleration of protons in supernova shock waves is a favored explanation for the origin of cosmic rays, however this mechanism fails for higher energies (Hillas 1984). An accurate enumeration of the total power output by the TeV and PeV sources will be a step toward direct verification of the shock wave hypothesis and may lead to identification of other sources of VHE/UHE cosmic rays.

It is now clear that some of the VHE/UHE sources contain rapidly spinning, highly magnetized neutron stars, in which a substantial fraction of the energy output is in the form of relativistic beams. A well developed TeV astronomy should help determine the particle identify of the beams (electronic or hadronic) and illuminate the nature of the various acceleration mechanisms which produce the beams.

Progress in understanding relativistic objects will be maximized through a multi-wavelength approach in which observations at satellite energies are complemented by coordinated ground-based observations.

II. THE ATMOSPHERIC CHERENKOV TECHNIQUE

A photon with an energy above a few tens of GeV may be detected on the ground by means of the air shower Cherenkov light. This light is emitted by those charged particles in the shower which have velocities, v/c , greater than $1/n$ where n is the index of refraction of the atmosphere. For a 10^{12} eV shower approximately 10^6 Cherenkov photons are emitted spread over a region on the ground of a few $\times 10^8$ cm 2 .

The information content of the Cherenkov photons is high quality both from the point-of-view of the Cherenkov photon statistics and because these photons are dominantly from the region of the shower's maximum development and therefore less subject to shower-to-shower fluctuations.

This information in principle allows air showers from gamma-rays and cosmic rays to be distinguished from one another, as illustrated by the Whipple Observatory Collaboration's detection of the Crab Nebula discussed below. Because of this feature the technique has the ability to prove that the shower primary is in fact a gamma-ray, and we can look forward to future improvements in the Cherenkov technique in which the unwanted cosmic ray background is reduced substantially beyond what has already been achieved.

Because of the large collection area per independent Cherenkov collection mirror, TeV detectors are intrinsically high-rate devices, with detection rates for the brightest sources of a few photons/minute and burst rates even higher. This feature can be used to search for pulsars that would be hidden at x-ray and radio-wave energies. The mean free path of gamma-rays is 5×10^{25} H-atoms/cm 2 vs $< 10^{22}$ for x-rays. Radio pulses from x-ray binaries may not escape due to plasma absorption. Thus there may be pulsars that are only detectable in gamma-rays. Recognition of this fact has motivated several groups to search for a possible pulsar associated with Cygnus X-3 (Chadwick et al. 1985 and Zyskin et al. 1987).

The high-rate capability can also be used to explore short time scale phenomena indicative of time varying acceleration and/or changes in beam-target geometry.

The ultimate capabilities of the atmospheric Cherenkov technique have not been fully explored. Most recently Hillas (1989) has shown that angular resolutions of 2 - 3 arc minutes are possible with the technique with an ideal imaging detector.

III. DETECTION OF THE CRAB NEBULA

The Whipple Observatory's gamma ray telescope consists of a 10 meter reflector in which an array of fast photomultipliers, located in the focal plane, is used to image individual air showers. Showers are detected at a rate of approximately 3 Hz, more than 99% of which are due to cosmic rays. The shower images are recorded and gamma ray candidates are selected in off-line analysis, using a procedure determined by Hillas (1985) from Monte Carlo simulations tailored to the Whipple instrument.

A simple moment analysis of the pattern of light is used in which second moments of the light around its centroid are used to derive size and orientation parameters for each shower image. Simulations and observations agree that in the original 37 element (0.5° pixel spacing) camera cosmic-ray background showers have a mean size of 1.0° (full-width half height) whereas gamma-ray showers have a mean size of 0.5° . Furthermore, gamma-ray showers are more elongated (except for showers whose axis falls within 50 meters of the reflector). The elongation is such that the major axis of the light is oriented preferentially radially from the center of the field-of-view. These differences can be summarized by saying that the Cherenkov light images from a gamma-ray source are more compact and point to the source.

Although six parameters were originally introduced by Hillas, one parameter, the "azwidth", appears to be more effective than any other single parameter and as effective as any combination of parameters. Azwidth is defined to be the rms width of the shower images in the azimuthal direction of the image plane.

With this parameter and with the cut values of azwidth as set in advance by the Hillas' simulations the Whipple group has published a 9σ detection of the Crab Nebula (Weekes et al. 1989) using a relatively coarse resolution camera (0.5° pixel separation) and, more recently, an independent 15σ detection (Lang et al. 1990) with a higher resolution camera (0.25° pixel).

The distribution of azwidth values for the 9σ detection (Weekes et al. 1989) is shown in figure 2b, with a comparison of the expected behavior of azwidth values for simulated gamma-ray and proton-initiated showers in figure 2a. The peak of the observed azwidth distribution, near 0.4° , is in agreement with the simulations for proton showers. The only significant difference in the on-source and off-source distributions is in the region of small azwidth as expected if the on-source region is a source of TeV gamma rays. The difference of the two distributions in this region is shown in the inset to figure 2b.

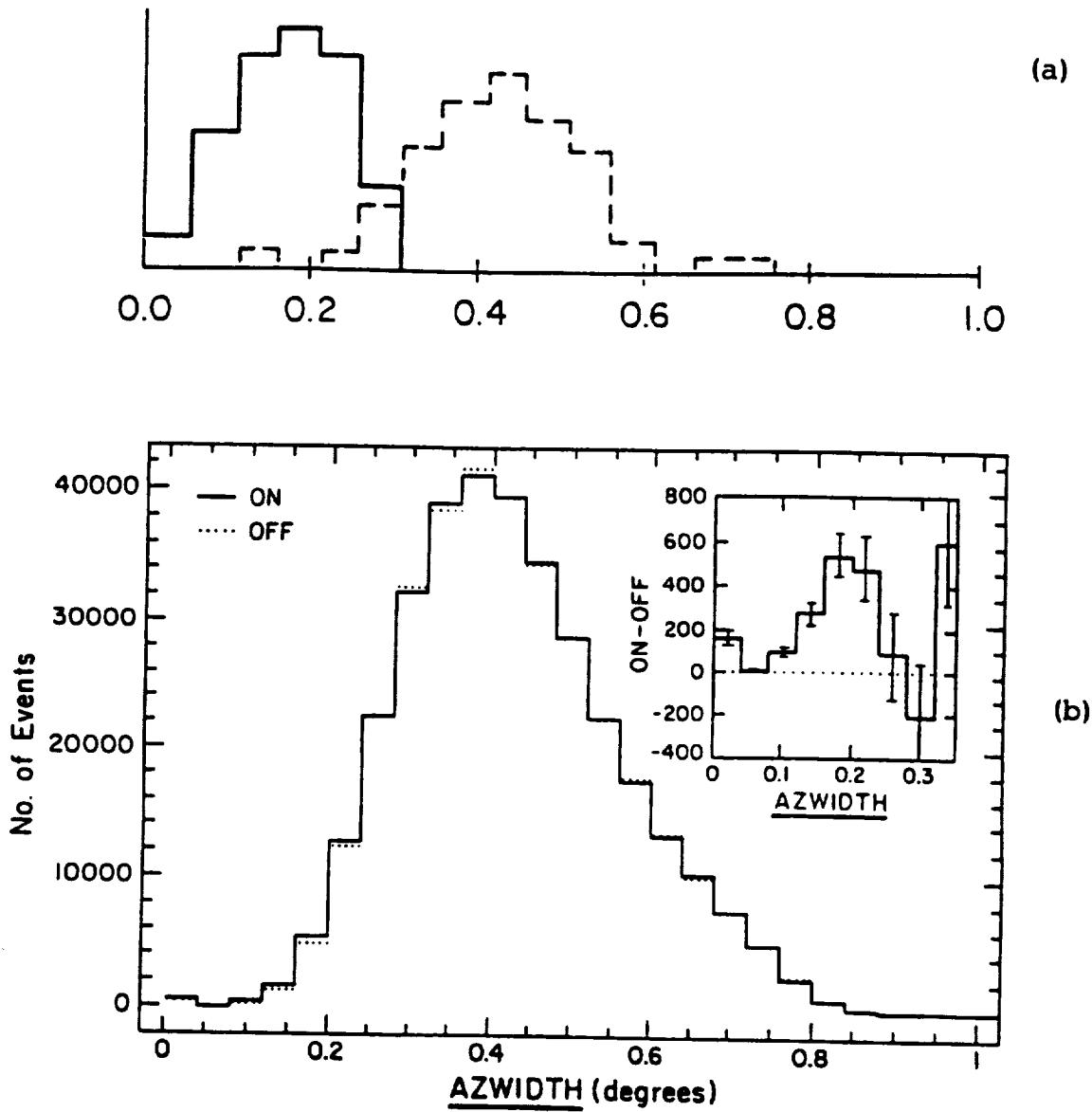


Figure 2. (a) Distribution of AZWIDTH for simulated shower events (Hillas 1985): gamma-ray initiated showers, solid line (-); proton-initiated showers, dashed line (--); (b) Distribution of AZWIDTH for observed showers (Weekes et al. 1989). On source, solid line (-); off source, dotted (...). The difference in the two distributions is shown in the inset.

The Whipple's observations of the Crab Nebula have been subjected to a number of tests for possible systematic errors. For example, the signal does not depend on the order of the comparison between on-source and off-source regions. If the signal were noise related then it should be most apparent for showers with total light near threshold; it is not. There is a third magnitude star, Zeta Tauris, in the field of view of

the camera. In order to test for the effect of such a star on the Cherenkov images, a control region of the sky was chosen in which a third magnitude star was present as a false "on-Crab" region whereas no such star was present in the false "off-Crab" region. Comparison of the two false regions showed no excess either before or after the azwidth selection was made. Many other tests were made, as described in Weekes et al. (1989), with similar results. The Whipple's detection of the Crab Nebula appears to be a solid result of TeV astronomy.

Independent support for this result comes from the University of Michigan's observations. With twin 11 meter diameter mirrors, each with 7 element cameras, Akerlof et al. (1989) have a 5.8σ detection of the Crab Nebula produced by the application of imaging type cuts on a raw 2.3σ excess.

There is no evidence for time variability on a month-a-month basis in the Whipple's Crab signals. If we assume little or no variation over two decades it is meaningful to compare the earliest Whipple Crab detection (Fazio et al. 1972) without imaging with the more recent imaging results. Table I gives the comparison. As the reader can see, an overall gain in sensitivity of a factor of 10 has been achieved, i.e. the signal/background has improved by a factor of 100.

TABLE I
SENSITIVITIES OF DIFFERENT DETECTORS
FOR OBSERVATIONS OF CRAB NEBULA

Date	Imaging	Time on Source (h)	σ	Gain Factor vs. non-imaging system	References
1968-72	no	150	3	1	Fazio et al. 1972
1986-88	yes(0.5° pixel)	80	9	4	Weekes et al. 1989
1988-89	yes(0.25° pixel)	30	15	10	Lang et al. 1990

IV. SIGNIFICANCE

The bulk of the radiation reported by both the Whipple group (Weekes et al. 1989) and by the University of Michigan group (Akerlof et al. 1989) is not pulsed at the Crab pulsar frequency. The integral photon flux values from these measurements is shown in figure 3, along with the extrapolations from lower energies of the COS-B results (Clear, et al. 1987) for both the pulsed and unpulsed components. The TeV points falls approximately midway between the extrapolations of the lower energy observations.

The TeV observations and a synchrotron-self Compton model for TeV emission (Rieke and Weekes 1969) constrain the magnetic field of the Nebula to be approximately what is expected on the basis of energy equipartition arguments, namely $\sim 6 \times 10^{-4}$ G. Measurements of the differential energy spectrum of the source in this spectral region should be forthcoming, and, in the context of the synchrotron-self Compton model, determine the spectral behavior of the parent population of relativistic electrons.

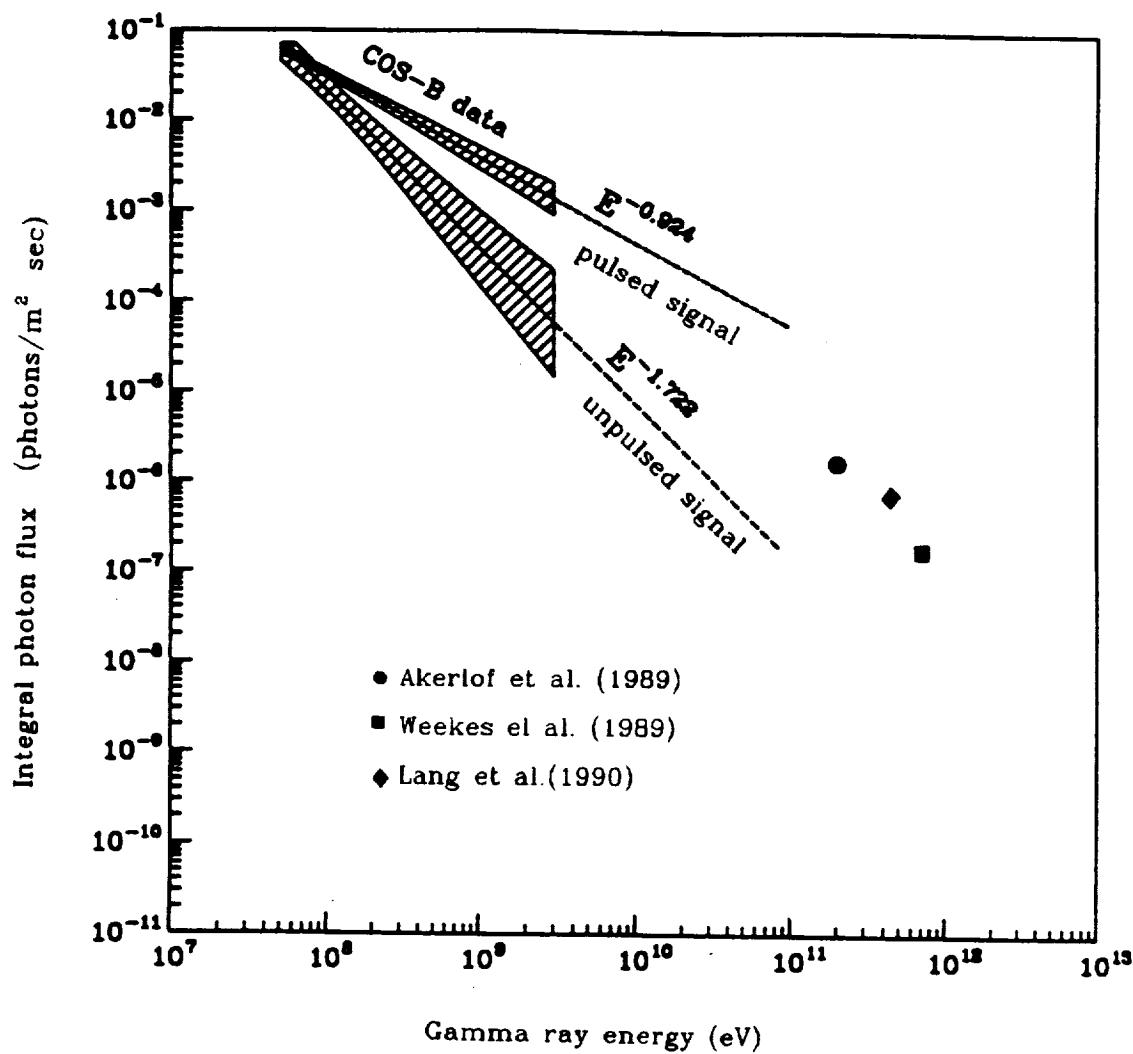


Figure 3. The gamma-ray energy spectrum of the Crab nebula and pulsar above 70 MeV.

V. OTHER SOURCES

More than a dozen other sources have been reported at both TeV and PeV energies. See Weekes (1988) for a recent compilation. A potential major embarrassment of the field of VHE/UHE gamma ray astronomy is that so far the Crab Nebula is the only source for which the signals behave as expected of photons. The optimist would say that this strong evidence that "new physics" is afoot. The pessimist/realist would say that this is strong evidence that no source (other than the Crab) has been seen. Bonnet-Bidaud and Chardin (1988) have expressed this latter view in their review of Cygnus X-3. My own view is that the number of independent sightings of such binary sources as Cygnus X-3, Hercules X-1, and Vela X-1 are too

numerous and too strong to ignore. The question of "new physics", however, is a much bigger question and one that is a long way from being proved. As someone said recently, "extraordinary claims require extraordinary evidence." The extraordinary evidence is not at hand (yet).

The failure of other source signals to behave as expected of photons has been emphasized by Hillas (1987) at the Moscow ICRC. At air shower energies two traditional methods of reducing the background exist, one of which (muon content) is on a secure calculational footing; however, the other method, which uses age cuts, is not.

Calculations (Protheroe and Turver 1979; Stanev, Vankov, and Halzen 1985) show that gamma-ray showers are relatively poor in muons (10% or less of the content of proton showers of the same size); thus a cut on muon poor showers should improve sensitivity. In fact the original Cygnus X-3 PeV detection (Samorski and Stamm 1983) showed signals with a muon content roughly equal to that of background cosmic ray showers.

The other selection technique used at air shower energies is an age parameter cut. The use of this parameter has been called into question by simulation of PeV gamma-ray and proton air showers by Hillas (1987). These simulations make two points: 1) age is a relatively poor discriminant between gamma-ray and cosmic-ray showers, and 2) what discrimination exists is such that gamma-ray showers are younger on average rather than older than the cosmic-ray background showers of the same energy. The selection of Samorski and Stamm picked showers with age values greater than 1.3, relatively old and inconsistent with Monte Carlo expectations for gamma-rays.

The CYGNUS group, operating an air shower array at Los Alamos National Laboratory, has reported evidence for burst signals from Hercules X-1 (Dingus et al. 1988) on a time scale of 30 minutes. The apparatus is sensitive to air showers of energies greater than 50 TeV. Their signals are anomalous in that they are not poor in muons.

Signals reported by the Whipple Collaboration at TeV energies from the direction of Hercules X-1 (Reynolds et al 1990) are also anomalous in that they disappear when the azwidth imaging cut is applied to them.

VI. TeV ASTRONOMY IN THE GRO ERA

The sensitivities of detectors operating in the VHE/UHE energy range are improving. In addition to the Whipple instrument Cherenkov imaging detectors exist at the Crimean Astrophysical Observatory (operational 1989) and the Yerevan Physical Institute (construction begun 1988), and plans for a high angular resolution instrument have been proposed by the JANZOS collaboration to be located in Australia. At higher energies the CYGNUS collaboration is extending their array to a ground coverage area of $0.8 \times 10^5 \text{ m}^2$ and the Chicago, Michigan, Utah installation will have a coverage of $2.5 \times 10^5 \text{ m}^2$ within two years.

The Whipple instrument will be upgraded with the addition of a second reflector 11 meters in diameter (GRANITE project). It should be complete and ready to take data in early 1991. Figure 4 shows the sensitivities of the new ground-based instruments in comparison with the sensitivities expected of the GRO instruments. Note that the vertical scale of the differential sensitivity has been multiplied by the 2.5 power of the gamma-ray energy. As one can see there is a good match by the ground-based instruments to the sensitivities of GRO instruments.

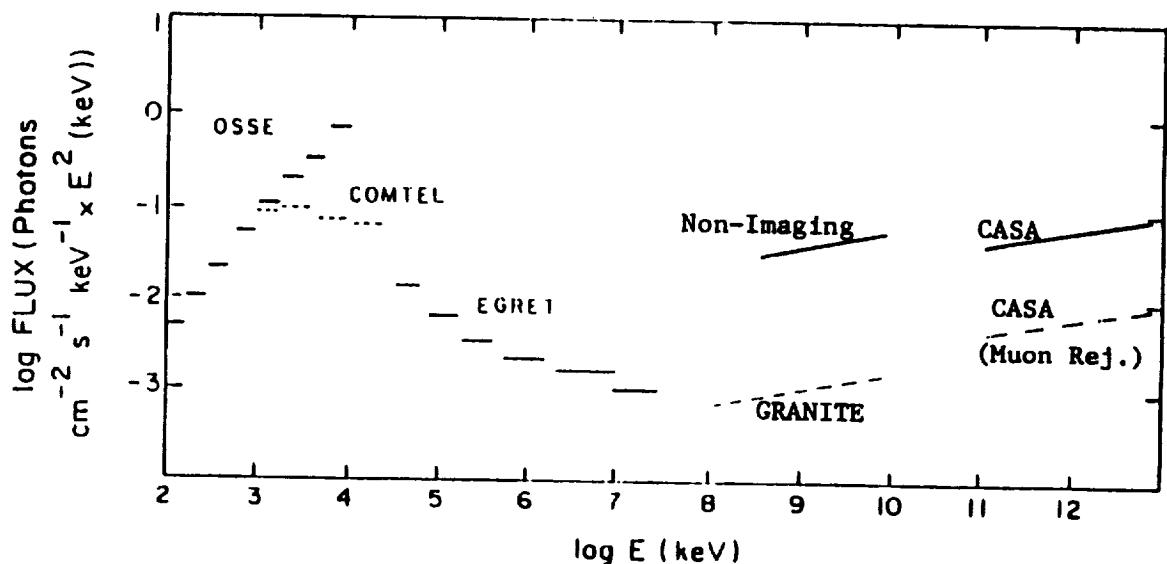


Figure 4. Minimum flux sensitivity in different bands of the gamma-ray spectrum.

A vigorous program of coordinated observations between GRO and the ground-based Cherenkov receivers is anticipated. If GRO is pointed at a target of mutual interest during a dark moon period and the source transits near midnight, then the on-time of Cherenkov receivers can approach 25% under the assumption of good weather. Thus a good overlap in simultaneous observations can be anticipated. Of course, for a reasonably steady source like the Crab Nebula, simultaneity is not necessary. For the Crab, many interesting questions regarding spectral changes for the pulsed and unpulsed components can be addressed by combining data from EGRET and the most sensitive of the Cherenkov receivers.

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DISCUSSION

Carl Fichtel:

Will any of the other Cerenkov observatories have either a fine grid of photomultipliers comparable to the Whipple one or two telescope system?

Dick Lamb:

The Crimean Astrophysical Observatory has a Cherenkov imaging system with a 37-element camera which is essentially ready to begin observations. An imaging system is under construction at the Yereban Physical Institute, and the JANZOS collaboration plans a high resolution camera (pixel size 0.15°) for operation in Australia.

R. Buccheri:

Does Whipple Observatory confirm the 12.6 ms pulsar detected by the Durham group in the Cyg X-3 source?

Dick Lamb:

The Whipple Observatory collaboration does not confirm either the 12.6 ms pulsation reported by Durham nor a 9.22 ms pulsation reported by the Crimean Astrophysical Observatory.

